A DESIGN OF THERMIONIC ELECTRON GUN FOR TRAVELING WAVE ELECTRON- LINAC IN ORDER TO INJECT BEAM INTO BOOSTER SYNCHROTRON ACCELERATOR

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Abstract

Applying computational codes functioning on the basis of methods such as Finite Integration caused the designing of different parts of an accelerator to be done faster and with more precision. New software validity is evaluated compared with analytical relations and practical results. This research aims to design an appropriate structure for thermionic electron gun of travelling wave electron-linac to be used to inject beam into synchrotron accelerators. First, a simple structure of an electron gun used in TWT tube was simulated, and the parameters such as current, perveance, beam waist position, beam waist radius, and also the electric potential variation in the anode-cathode distance and the electric field of anode aperture were compared by experimental results and analytic relations. After verifying the software validation, a design of an electron gun with energy and current respectively, 200 keV, 18 A and also initial beam radius of 8mm and minimum beam radius of 3.4 mm situated at the distance of 67.44mm from the cathode, was presented.

INTRODUCTION

Electron gun is the primary source in pre-accelerator of synchrotron facilities. The emission mechanisms of electron are: thermionic emission, field emission, photoelectric emission and secondary electron emission. Thermionic electron gun is the most prevalent gun [1].

The gun current rate according to the gun geometry represents gun perveance which is expressed as $P=I/V_0^{3/2}$(μperv). Thus, thermionic electron guns are classified as; Low- perveance P<<0.6μperv, moderate-perveance P≤1μperv, and high- perveance (P>1μperv) [3]. Limitations such as lack of experience and expensive manufacturing make it inevitable to use software in order to evaluate their operation. Validation of such software is the first step of using them. Among the important parameters in designing an electron gun are: current I, perveance P, beam waist position z_m, and beam waist radius r_m. The current is dependent to perveance and the applied voltage. The perveance is just dependent to the geometry and the type of the particle. The beam waist radius is defined the radius containing 95% of beam current. Accuracy of measurement and control this quantity is special significance to achieve the desired final emittance in large accelerator. The beam waist position is the distance between the beam waist radius and head cathode. It is inevitable to use steering magnet and solenoid in order to steer the beam after its exit of the gun. The magnetic field edge should be located exactly at the beam waist position to achieve maximum stability and minimum current density loss [3, 4].

METHOD

Finite integrated method is applied to solve equations in CST software. In order to validate this software was chosen a high perveance electron gun with energy 8keV. Figure 1, shows the analytical and simulated geometry of spherical diodes. In this figure, R_c is radii of curvature of the cathode, R_a is radii of curvature of the anode, and R is radial position between concentric spheres.

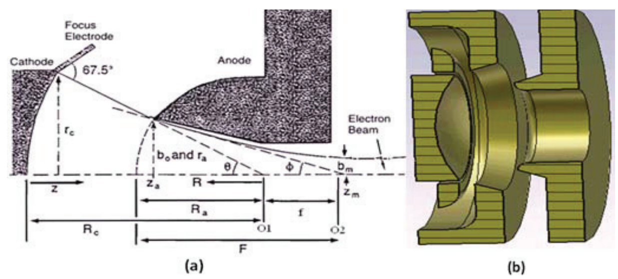

Figure 1: a) Spherical diodes analytic geometry [4] b) High-perveance gun geometry.

The Poisson's equation is expressed in the form of Eq. (1), source voltage is zero and anode voltage (V):

$$\nabla^2 V = \frac{1}{R^2}\frac{d}{dR}\left(R^2\frac{dV}{dR}\right) = \frac{\rho}{\varepsilon_0} \tag{1}$$

Definition of parameters $\gamma=\ln(R_c/R_a)$ and $f(\gamma)=-\alpha(R_c/R)$ by Langmuir and Blodgett as Eq. (2), conical portion current with half angle θ in the spherical diode is: [3]

$$f(\gamma) = -\alpha(R_c/R) = \gamma + 0.3\gamma^2 + 0.075\gamma^3 + 0.01432\gamma^4 \tag{2}$$

$$I = \frac{8\pi\varepsilon_0}{9R^2}\sqrt{\frac{2e}{m_e}}(1-\cos\theta)\frac{V^{3/2}}{\left[-\alpha(R_c/R)\right]^2} \tag{3}$$

With having I, the voltage in each point cathode-anode will be calculated. The electric field near the anode is obtained from Eq. (4) in which $df(\gamma)/d\gamma=1+0.6\gamma+0.225\gamma^2+0.0573\gamma^3+0.0108\gamma^4$.

$$E_a = \frac{4V_a}{3(-\alpha(R_c/R))}\frac{1}{R^2}\frac{df(\gamma)}{d\gamma} \tag{4}$$

In order to proper beam injection to the magnetic converging structure, it is necessary to determine the exact quantities: beam radius at entrance into anode aperture $b_0=r_c\exp(-\gamma)$, beam waist position $z_m=z_a+(b_m/A).[1.914(B)^{1/2}+0.230(B)+0.0107(B)^2]$, and its radius $b_m=b_0\exp([-(\tan\varphi/A)]^2)$, where $B=(b_0/b_m)-1$ $\tan\varphi=b_0/F$, $A=0.174(P)^{1/2}$ [4]. In these gun, the system geometry characteristics are r_c=3.6mm, R_c=6.8mm, R_a=3.3mm, and angle θ=32.4°. Thereupon, the required parameters for analytic calculation will be equal to: γ=0.718, f(γ)=0.905, df(γ)/dγ=1.57, and tanφ=0.130. The

CST simulation results are shown in Figure 2. A comparison between simulation and analytical results is presented in Table 1. Experimental and simulation results were compared according to Table 2. Figure 3, shows the potential change in anode- cathode distance, 4.9mm.

Table 1: Comparison between Simulation and Analytical Results

Parameter	I (A)	P (μperv)	z_m (mm)	b_m (mm)	E_a (MV/m)
Simulation Results	1.93	2.70	9.12	1.51	5.44
Analytical Relations	2.00	2.80	9.66	1.44	5.58
Variation	3.5%	3.6%	5.5%	4.8%	2.5%

Table 2: Comparison between Experimental Results and Simulation

Parameter	Simulation Results	Experimental Results	Variation
Current	1.93(A)	(1.9-2) (A)	1.2%
Perveance	2.7(μperv)	(2.6-2.8) (μperv)	0.9%

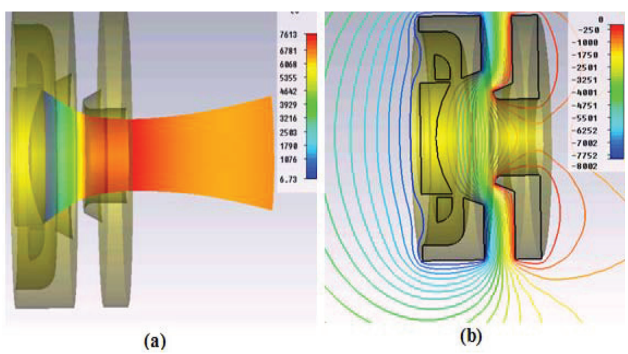

Figure 2: a) Electron trajectory, b) Equipotential lines.

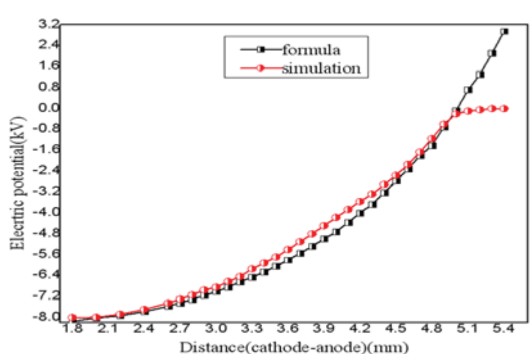

Figure 3: Electric potential variation.

DESIGN PROCEDURE

To determine the electrode prototype using analytic relations, the parameters like voltage, current, cathode current density and waist beam radius must be specified [3]. Afterward, the initial design is simulated and the designed geometry is optimized regarding the desired characteristics. The designed electron gun is a diode type and capable of generating 18.2A current at the voltage 200keV. These gun characteristics are obtained from EIMAC Y796 gun designed for SPRING synchrotron, according to Table 3, only with this difference that this gun is of diode type. The reason for this choice is grid manufacturing difficulties in Iran.

Table 3: EIMAC Y796 Electron Gun Characteristics

Parameter	I	P	V	J	b_m	d_{ac}
Value	18.2 A	0.2 μperv	0.2 MV	9.11 A/cm^2	3.4 mm	30 mm

Theoretical Calculations

The gun design is based on the Pierce spherical diode. According the Figure 4 b), the gun is divided to 3 regions. The first region consists of spherical cathode and focusing electrode with identical curvature centre with cathode. Because of the anode aperture, the equipotential surfaces are bent into the anode aperture and make the beam diverge in region 2. There is no electric field in drifting region, 3, and the electron motion is affected by space charge forces. The calculations will continue until the electron divergence affected by negative anode lens in region 2, $\tan\phi_2 = \frac{b_0}{R_a}\left[1 - \frac{1.25}{3(-\alpha)}\frac{df(\gamma)}{d\gamma}\right]$, is close to electron divergence in drifting region 3, $\tan\phi_3 = 0.174\sqrt{P}\left(\sqrt{\ln\frac{b_0}{b_m}}\right)$.

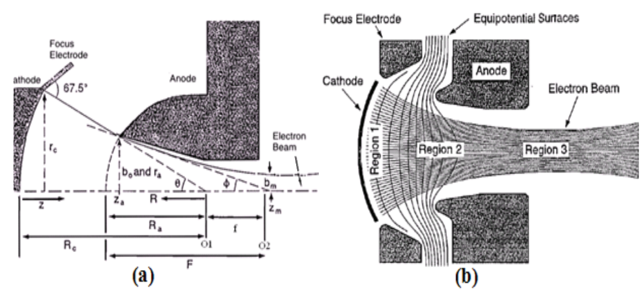

Figure 4: a) Pierce design geometry. b) Trajectory and different regions in this design [2].

The parameters (−α), γ, and df(γ)/dγ need to be calculated to determine the above equations. In design process, the parameter $(-\alpha)=(14.67\times10^{-6}\times(1-\cos(\theta))/P)^{1/2}$ must be specified. Afterward according Eq. (5) , (6), the other parameters like γ, df(γ)/dγ are defined using (−α).

$$\gamma=(-\alpha)-0.275(-\alpha)^2+0.06(-\alpha)^3-0.006(-\alpha)^4 \tag{5}$$

$$df(\gamma)/d\gamma = 1+0.6\gamma+0.225\gamma^2+0.0573\gamma^3+0.0108\,\gamma^4 \tag{6}$$

According Table 3, $r_c=(18.2/\pi(9.11))^{1/2}=8$mm was obtained. The cathode and anode curvature radius are computable by $R_c=r_c/\sin\theta$ and $R_a=R_ce^{-\gamma}$ respectively. The beam radii at entrance into anode aperture is $b_0=r_ce^{-\gamma}$. The design processes is carried on by half angle θ guess and continue the calculations until the quantities $\tan\varphi_2$ and $\tan\varphi_3$ are approached to each other [4]. Regarding the low perveance of this gun, the initial angle is guessed to be $\theta=10^\circ$. But because of large differences between divergence angles, $\tan\varphi_2$ and $\tan\varphi_3$, we had to change the angle. Thus the calculations are repeated for $\theta=11^\circ$. Table

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4 summarizes the computation process. Should be noted that according to Figure 4 a), beam radius at entrance into anode aperture b_0, is always larger than the waist beam radius b_m=3.4mm. But this rule is violated for mentioned angle, therefore calculations were repeated for θ<10.

According the results Table 4, angle θ=8° has the slightest difference between two divergence angles. Hence, the initial design was based on these parameters. The beam waist position from cathode is equal to z_m=67.44mm.

Table 4: Design Process for Various θ s

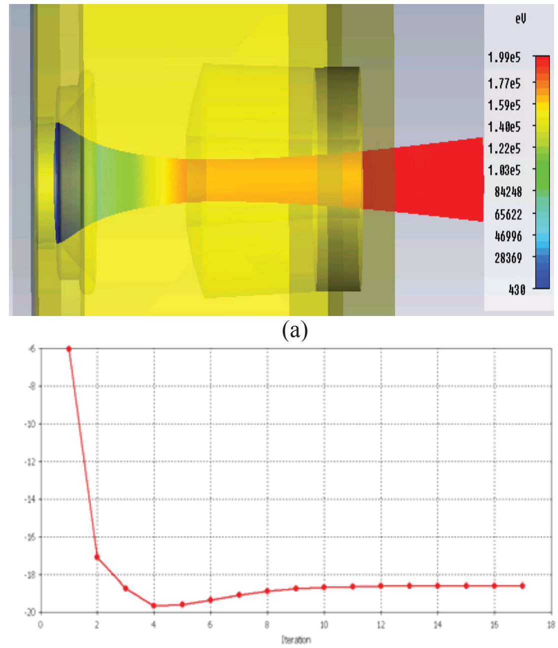
θ°	10°	11°	9.5°	8.5°	8°	7.6°
(−α)	1.05	1.16	1.02	0.89	0.84	0.82
γ	0.81	0.87	0.78	0.71	0.68	0.66
$e^{-\gamma}$	0.44	0.41	0.46	0.48	0.50	0.51
R_c(mm)	46.07	42.1	48.48	54.13	57.48	58.94
R_a(mm)	20.44	17.6	22.21	26.46	29.06	30.22
b_0(mm)	3.55	3.34	3.66	3.91	4.04	4.10
df(γ)/dγ	1.67	−	1.63	1.59	1.53	1.52
$\tan\varphi_2$	0.059	−	0.053	0.040	0.033	0.031
$\tan\varphi_3$	0.016	−	0.021	0.029	0.032	0.034
Variation	73%	−	60%	28%	3.8%	7.3%

Anode aperture is the next essential parameter in design process. The initial thermal velocity of electrons and focusing electrode length L, were not considered in analytic computation of beam radii at entrance into anode aperture. This makes the actual beam radius bigger than b_0, usually supposed to be $1.2b_0$. According the Pierce design, the anode shape would be a conical with (1.5−1.2) b_0 radius [3]. On the other hand, according to the Pierce design, cone-shaped focusing electrode with 67.5° angle with respect to the cathode edge and equipotential with its is considered. In simulation based on analytical relations because of ignoring the presence of these electrodes, it is impossible to access the desired parameters and the effective parameters will change with the electrode length change [2]. The main result of this simulation is that when the electrode's length increases, the total current will decrease. Also beam waist position would be closer to cathode and its radius would decrease. After the initial design, the optimized electrode length to achieve the desired beam characteristics was equal to 8.3mm. In Table 5 summarized some geometric characteristics.

Eventually the electron gun simulation results with 200keV energy are showed in Figure 5 and these results comparison with the analytical results are listed in Table 6.

Table 5: Geometric Characteristics of the Designed Gun (0.2MeV−18.2A)

Parameter	R_c (mm)	r_c (mm)	R_a (mm)	r_a (mm)	L (mm)
Value	57.48	8.00	29.06	6.07	8.3
Parameter	d_{ac} (mm)	b_0 (mm)	b_m (mm)	z_m (mm)	φ
Value	30	4.04	3.40	67.4	1.93°



(a)

(b)

Figure 5: a) Trajectory, b) Total output current.

Table 6: Simulation and Analytical Result Comparison in Designed Gun

Parameter	I(A)	P(μperv)	z_m(mm)	b_m (mm)
Simulation Results	18.6	0.207	68.0	3.62
Analytical Relations	18.2	0.203	67.4	3.40
Variation	2.2%	1.9%	0.8%	6.4%

CONCLUSION

In this paper, validation of CST software in design of electron gun was evaluated. Then, we basically designed a thermionic electron gun with spherical structure to be utilized in an electron linac. Cathode radius of 8mm, anode aperture radius of 6.07mm, and total structure length of 67mm are some geometrical results obtained from the analytical relations. Meanwhile, regarding the diverging effects of the anode aperture, an electrostatic focusing electrode is necessary. This electrode with the length of 8.3mm and the angle of 67.5° with respect to the cathode edge is caused the beam dispersion angle 1.93° at the focal point. Finally, the values of the effective parameters including current, perveance, beam waist radius, and its position by simulating the aforementioned geometry were obtained 18.6A, 0.207μperv, 3.62mm, and 68mm, respectively.

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